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ADVANCED TECHNOLOGY PROGRAM CASE STUDY: The Development of Advanced Technologies and Systems for Controlling Dimensional Variation in Automobile Body Manufacturing

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ADVANCED TECHNOLOGY PROGRAM CASE STUDY: The Development of Advanced Technologies and Systems for Controlling Dimensional Variation in Automobile Body Manufacturing

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Executive Summary

The Advanced Technology Program (ATP) is a unique partnership in which the federal government and private industry cooperatively fund research and development projects that have high technical risk and commensurate large potential for creating broad-based U.S. economic benefits. The Development of Advanced Technologies and Systems for Controlling Dimensional Variation in Automobile Body Manufacturing is a research project whose cost has been shared by industry and the ATP. The project early on was dubbed the "2mm project" in reference to its goal of matching and pushing beyond the then world-class standard for dimensional control in automobiles achieved by some Japanese and European producers. The project was performed by a joint venture including the Auto Body Consortium (ABC), a coalition of small- to medium-sized companies that supply engineering services and tooling for automobile body assembly; two universities; and two automobile manufacturers. Nearly 65 percent of the project's funding has been provided by the members of the joint venture. ATP's funding was used to expand the university research effort.

The ATP evaluates the projects it funds to ensure that they are on track , to determine their short- and longer-run impacts, and to improve the Program's effectiveness. The 1993 Government Performance and Results Act (GPRA) requires evaluation of federal programs, and the ATP has emphasized evaluation from its start in 1990. In support of that effort, the ATP uses the services of a variety of academic and consulting economists and other experts in evaluation.

CONSAD Research Corporation was engaged by the ATP to perform a case-study analysis of the 2mm Project. For this analysis, CONSAD first investigated the effects of the ATP-sponsored project at the firm level to determine the technological changes that resulted from the project; the role played by the ATP; and the nature of the direct economic impacts that are expected to result from the technological changes. The results of this background investigation are reported in Part I of this report. The information obtained in the background investigation was then used to estimate the economic impacts of the project, omitting at this time possible impacts from future adoption of the technology by user industries other than the automobile industry. The methodology and approach to data collection used to estimate the economic impacts are described in Part II of this report. The projected economic impacts, the limitations of the study, and recommendations for future case studies of ATP projects are also presented in Part II.

This case study analysis represented a learning experience for the ATP and CONSAD with regard to estimating the impacts of a new manufacturing technology for which there is only preliminary information characterizing industry experience. Industry experience is limited at this time because the R&D project was completed only recently, and more remains to be done. The methodology used relied on a microeconomic investigation of the impacts of the project on firms that have adopted the technology on an experimental basis for subsequent macroeconomic modeling of the impacts on the national economy. The estimated impacts are rough approximations based on a number of assumptions.

A significant component of the methodology CONSAD used to perform the economic impact assessment was the use of macroeconomic interindustry modeling to produce preliminary estimates of the impacts. For this study, CONSAD applied the Regional Economic Models, Inc. (REMI) Economic and Demographic Forecasting and Simulation 53-Sector (EDFS-53) model in conjunction with analysis based on the input-output (I-O) tables of the Bureau of Economic Analysis (BEA). **Application of a macroeconomic interindustry model, such as the REMI model, to project broad-based effects of microeconomic changes resulting from technological advancement is experimental in nature.** The model was run with changed parameter values suggested by the investigation of the effects of the ATP-sponsored project at the firm level. Some of the identified effects did not lend themselves to analysis within the REMI model, and were evaluated outside the model. Furthermore, some potential effects of the ATP-

sponsored project were considered too uncertain at this early stage to attempt quantification and, therefore, were omitted from the analysis. The results of the macroeconomic analysis provide a very preliminary projection of future national economic impacts of the ATP-sponsored project.

The main findings of CONSAD's analysis are:

- The project's technical goal of reducing dimensional variation in automobiles to, or below, 2.0 mm was achieved, and the results to date suggest that the project will generate benefits many times greater than the project costs by the year 2000.

- The technologies and the methodology developed by the 2mm Project directly result in the following four types of benefits:

  (1) decreased production costs;
  (2) decreased product maintenance costs;
  (3) improved product quality; and
  (4) reduced time required to launch new products or product models.

- The ATP served as an essential enabler for this technological advance to be achieved in a timely way. In the absence of the ATP, impediments to cooperation among the joint venture members would have prevented this project of broad-scope from being undertaken. It is interesting to note that none of the joint venture members received any funds directly from ATP. The ATP funds were pooled among the joint venture members and used to contract university research on a scale and of a scope beyond what the majority of the joint venture's small- and medium-sized companies could fund on their own. The companies funded their own direct participation in the project, contributing cash and in-kind labor.

- The 2mm Project research strategy took a coordinated, systems approach in which many of the factors that contribute to dimensional variation in automobile bodies were studied concurrently by distinct project teams within the structure of an integrated research design. The 2mm Project has established a metrology-based automotive body assembly process resulting in reduced dimensional variation in automobile bodies. The collaboration and combined expertise of automobile body assembly tooling suppliers, engineering service companies, automobile manufacturers' engineers and line operators, and research universities, have been essential to achieving the technical goals of the project.

- At the time the proposal was submitted, 2.0 mm of total variation in automobile body-in-white openings was the world-class benchmark for automobile body fit. The technologies and methodologies developed as a result of the project have enabled U.S. automobile manufacturers, working with their suppliers, to achieve and go beyond the 2.0 mm benchmark in a cost-effective manner, and, equally significant, has positioned them to reduce the dimensional variation of their automobile bodies even further in the future.

- As of December, 1995, the goal of reducing the dimensional variation of automobile bodies to 2.0 mm had been achieved or surpassed in five U.S. assembly plants that produce, in total, more than 1 million automobiles and light trucks annually. Industry experts anticipate that the results of the 2mm Project will be adopted in all U.S. assembly plants operated by General Motors (GM) and Chrysler within five years. Together, GM and Chrysler produce approximately 48 percent of the cars and light trucks sold in America.

- To date, the net reduction in production costs from implementing the results of the 2mm Project at an automotive assembly plant is estimated to be approximately $10 to $25 per vehicle (e.g., production costs savings per car less the cost per car of implementing the new dimensional control technology). When adopted by all domestic GM and Chrysler assembly plants, the estimated total savings in net production cost, based on a combined annual forecast of 6.5 million vehicles, is on the order of $65 million to $160 million per year. These production cost savings will provide the automobile manufacturers increased flexibility in applying pricing strategies that influence overall market share, profits, and competitive strength.

- Estimates of the average total decrease in maintenance costs from implementing the results of the 2mm Project range from $50 to $100 per vehicle. This represents an estimate of the total decrease in maintenance costs that will occur during the useful lifetime of the vehicle due to less wear and tear, less rust, and reductions in other problems associated with poor body fit. A portion of the savings will accrue to the automobile manufacturer during the vehicle's warranty period, and the remainder to the vehicle's owner after the warranty has expired. Using the combined GM and Chrysler annual production forecast above, the total potential maintenance cost savings range from $325 million to $650 million per year after full implementation of the improved dimensional control technologies and methodologies. This estimate assumes that the number of automobiles produced each year gives rise to a stream of annual savings which, in the steady state, is roughly equivalent to annual production multiplied by the life-time savings per car.

- Implementation of the results of the 2mm Project decreases the time required to launch new automobile models. The reduction in launch times has the potential to generate increases in the new models' sales during the introductory period when demand is typically high. Available information is insufficient at this time, however, to estimate the magnitude of the sales increase.

- According to experts, improvements in product quality due to the 2mm Project are expected to generate an increase in the combined market share of GM and Chrysler in the range of approximately 1.0 to 2.0 percent relative to what it would be without the quality improvement. (These rough estimates are based on comparisons with historical data on changes in market share for competing automobile models that were associated with quality improvements.)

- The estimated impact on the U. S. economy of quality improvement in automobiles resulting from the 2mm Project was projected in this analysis using the 53-sector macroeconomic interindustry model developed by Regional Economic Models, Inc. (REMI). The projections were based on the expert-predicted market-share shifts, adjusted for displacement of domestically produced automobiles by foreign-owned producers. Using the REMI model, it is projected that the enabled quality improvement in automobiles will stimulate an estimated increase in total U.S. economic output (including all industry sectors affected) in the year 2000 of more than $3 billion, and possibly higher, relative to what it would be without the quality improvement. Also using the REMI model, it is projected that the enabled quality improvement in automobiles will potentially stimulate thousands of new jobs in the U.S. economy as compared to what would happen without the quality improvement.

- It should be noted that the projections of impacts are for the <u>whole</u> U.S. economy due to quality improvement resulting from adoption of the 2mm technologies by automobile producers (not by other industries), taking into account inter-industry relationships.

- It should also be noted that the projected net economic gains rest on the assumption that there is sufficient slack in the economy for new jobs and output to be added without immediate constricting monetary policy to offset the gains.

- These estimates of total economic impact have a large variance due to uncertainty in the estimates of change in market share that will result from the change in product quality. In addition, there are a number of other assumptions that affect the estimated economic impacts and about which there is uncertainty, such as the rate of adoption of the technologies in automobile assembly plants.

- Although it is impossible to state with accuracy the total increase in GDP and the total number of jobs that will result by the year 2000 relative to what would have happened without the quality improvement, it is possible to develop an idea of potential magnitude. The preliminary estimates suggest that the potential economic impacts will be substantial for the domestic automobile industry and for the nation as a whole since many sectors of the economy are affected by gains in the automobile industry.

- While the 2mm technologies are being applied first in the automobile industry, they are also expected to be adaptable to other discrete manufacturing industries, including aerospace, appliances, and metal furniture. The technology transfer process has begun and is in its early stages. Reliable estimation of the economic impacts of the technologies in these other industries cannot be performed, however, until sufficient time has passed to assess adoption rates and consequences, and to collect pertinent data.

- The study and its findings have limitations. These include the following: possible biases in the estimates made by industry experts; uncertainty in characterizing the future rate of adoption of the new technologies by domestic automobile producers; uncertainty associated with the effects of quality changes on market share in the face of the dynamics of domestic and foreign automobile markets; the need for data considered proprietary by the companies involved; and the inability at this time to estimate the diffusion of the technologies to other industries. It was not possible within the budget constraints of this experimental case study analysis to perform additional analysis that might have enabled the refinement of existing estimates. With the passage of time, it should be possible to overcome some of these limitations, reduce uncertainty in the estimates, and provide a more comprehensive assessment of the economic impact of the 2mm Project.

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Part I: About the 2mm Project

1.0 INTRODUCTION

The Advanced Technology Program (ATP) of the National Institute of Standards and Technology (NIST) is a unique partnership of government and private industry that seeks to accelerate the development of high risk, enabling technologies with large potential for beneficially impacting the U.S. economy. The ATP provides multi-year funding to single companies and to industry-led joint ventures.[1]

One research project that was awarded ATP funding is the Development of Advanced Technologies and Systems for Controlling Dimensional Variation In Automobile Body Manufacturing ("The 2mm Project"). It was conducted by a joint venture comprised of a group of small- and medium-sized companies that supply assembly line equipment and consulting engineering services to automobile manufacturers and together form the Auto Body Consortium (ABC), consisting at the start of the project of eight members: APX International; ASC, Incorporated; Classic Design, Inc.; Detroit Center Tool, Inc; ISI Automation Products Group; Modern Engineering; Perceptron, Inc.; and Progressive Tool & Industries Company (PICO); plus the University of Michigan, Chrysler Motors Corporation, General Motors Corporation (GM), and Wayne State University as a subcontractor.

The 2mm Project's research effort involved developing technologies that will control dimensional variation among automobile bodies during assembly. At an "ideal" automobile assembly plant, the sizes of openings, surfaces, parts and subassemblies would be identical on each assembled automobile body. In a real assembly plant, these sizes differ from automobile body to automobile body. These differences in sizes are referred to as dimensional variation.

In addition to their application in automobile assembly, the technologies and processes that are being developed as part of the 2mm Project have potential application in the aerospace, appliance, metal furniture, and other industries that manufacture products which require the automated assembly of metal parts.

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[1] Single companies can receive up to $2 million of ATP funds over a period not to exceed three years. Single companies do not have to provide matching funds, but they are reimbursed for direct costs only. They must pay for all overhead and indirect costs. Joint ventures can be funded up to a maximum of five years, with no funding limit. A joint venture must provide more than 50 percent of the total funding. The joint venture's matching contribution can take the form of cash and in-kind support. The research projects that receive ATP awards are selected from proposals that are submitted as part of general or focused ATP competitions. General ATP competitions solicit research proposals from all technology areas. (See *ATP Proposal Preparation Kit* for more details about the program and selection criteria.) Focused ATP competitions concentrate on specific technology or business areas designated by ATP in response to industry white papers. (See *ATP Guide for Program Ideas* for more about focused programs.) Research proposals submitted during ATP competitions are evaluated in a rigorous peer review process on the basis of the technical merit of the proposed research effort, the potential for commercialization, and the estimated broad economic impacts that the results of the research will potentially achieve. Further evaluation of projects is conducted in the post-award period. (See Ruegg, *Guidelines for Economic Evaluation* and ATP's *Progress Report on the Impacts of an Industry-Government Technology Partnership* for more about ATP's evaluation program.)

The proposal for this research project was submitted as part of an ATP general competition in 1991. The research began in September of 1992 and was completed in January of 1996. A total of $4.860 million in funding was committed by ATP, and an additional $9.007 million in funding was committed by the joint venture.

The three stated goals of the 2mm Project were: (1) to achieve 2.0 mm variation for body-in-white (BIW) build, (2) to advance the understanding of the physical properties of sheet metal and the assembly of sheet metal parts, and (3) to enable the companies to perform the improvements on their own.

Body-in-white (BIW) is the term used to describe the partially completed automobile body before the powertrain, paint, exterior trim, and interior furnishings are installed. The BIW is composed of the underbody, side frames, roof, shelves and backpanel. The door, hood, and deck-lid panels are installed into the openings of the assembled BIW. Later, after painting, the windshield and back-light are installed into the appropriate openings. If the BIW openings, panels, or other subassemblies vary significantly from their specified dimensional values, the assembly process can become more complicated and time-consuming than ordinary. In some cases, a BIW may require custom manual work to allow the parts to be assembled properly. In addition, the overall fit and finish of the completed automobile may be compromised if the dimensional variation is large.

Fit and finish is a subjective measure of the "quality" of the assembled automobile in terms of the sizes of gaps between and the flushness of different surfaces. The automobile industry has an established standard procedure for measuring the total dimensional variation of the BIWs produced at an assembly plant. If the dimensional variation of a BIW is so large that it cannot be assembled properly, it may be removed from the assembly line and discarded.

Although some dimensional variation will always occur during automobile assembly, a goal of the automobile manufacturers is to design an assembly line system that accounts for the intrinsic variation in parts, subassemblies, and materials in a way that minimizes the total dimensional variation of the finished automobile body. The 2mm Project addressed the subject with expertise and experience from both industry and academia. The goal of the 2mm Project was to reduce the standard measure of total dimensional variation for assembly plants that adopt the project's technologies below 2.0 mm.

The technologies that were being developed by the 2mm Project require the use of real-time data from accurate measurement devices for many, and preferably all, of the BIWs in line during assembly. Existing technologies for measuring the variation in BIW openings from design specifications consist of using hand gauges, layout plates, or Coordinate Measurement Machines (CMM). These contact measurement approaches, however, have low throughput and cannot be used in line during the assembly process. In the last five to eight years, non-contact Optical Coordinate Measurement Machines (OCMMs) have become available which have higher throughput and can be used in line. The OCMMs are used to measure the dimensions of 50 to 100 features of the BIW, depending on the assembly plant and the particular automobile, in a process that takes less than forty seconds. The use of real-time measurement data from OCMMs is the key input to a number of the 2mm Project's tasks.

Reducing the total dimensional variation of automobile bodies during assembly has the potential of:

(1) reducing the cost of automobile production,

(2) improving the quality of the finished automobiles and thereby enhancing customer satisfaction and increasing future sales,

(3) reducing future maintenance costs to the automobile manufacturers by decreasing the amount of corrective work that is performed on automobiles while they are under factory warranty and reducing future maintenance costs to the automobile owners by decreasing the amount of corrective work that is performed on automobiles after the factory warranty has expired, and

(4) reducing the launch time for getting new automobile models to market.

Reduced variation across all automobile bodies during assembly results in reduced production costs associated with the labor-intensive reworking of the BIW, or the customized fitting of panels into openings that are not properly dimensioned. An assembly line that produces BIWs without substantial dimensional variation does not require work stations dedicated to reworking activities. In addition, some automobile assembly plants currently station partially assembled BIWs, or "clones," at points in the assembly line where they can be used to replace BIWs with unsatisfactorily large dimensional variation. The use of clones averts the need for stopping the assembly line to accommodate individual BIWs with large dimensional variation, but adds to the total cost of assembly. Most notably, when changes are made to the design or manufacture of the automobile, clones intended for the existing design typically are discarded. Reducing dimensional variation reduces the need for clones.

One obvious result of reducing dimensional variation in BIW assembly is the improved quality of performance and appearance of the finished product. When the features of the BIW are properly dimensioned, and panels and windows fit properly into the corresponding openings, the completed automobile will have less water leakage, a quieter ride due to less wind and body noise, better fitting exterior and interior trim, a more solid and substantial feel, and a longer product life due to the reduced effects of corrosion and wear. Improvements in product quality also result in fewer problems arising during the lifetime of the automobile, and thus reduced need for service or repairs both during and after the factory warranty period.

An additional effect of dimensional variation on the automobile industry derives from its impact on the launch time when automobile assembly plants are newly opened or are re-tooled to produce new automobile models. During the launch of a new automobile model, considerable time is spent working out the bugs in the new assembly line equipment. Automobile manufacturers cannot begin to send products to dealers until problems associated with the assembly line are resolved and the dimensional variation of the bodies being produced is satisfactorily controlled. During this start-up period, the demand for the new automobile model is typically high. Shortages of vehicles during the early portion of the production run of a new automobile model has, on occasion, resulted in millions of dollars in lost sales. Thus, the technical results of the 2mm Project are potentially very important to automobile manufacturers during the launch of new models, as well as during the continuous operation of the assembly plants.

Automobiles produced by Japanese companies are generally perceived by the public to have higher quality than American cars. A report by J.D. Powers placed eight automobile models produced by Japanese manufacturers among the ten best automobiles ranked in terms of initial quality and customer satisfaction.[2] Most Japanese manufacturers currently operate their U.S. and foreign assembly plants at or below 2.0 mm of total dimensional variation. Automobile industry experts believe that the U.S. market share of U.S.-made automobiles would increase if their perceived quality were to match or exceed that of Japanese cars.

For the assembly plants operated by U.S. automobile manufacturers to match the performance of Japanese plants, improvements solely in manufacturing technology likely will not be sufficient.

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[2] J.D. Power and Associates, *New Car Initial Quality Study, 1995.*

Changes in operational practices and "corporate culture" probably are also needed. In general, assembly plant engineers and line operators often are reluctant to trust and accept new technologies and operational practices that they have not been involved in developing. There generally is less resistance to innovation when people have a sense of ownership of the new technologies and practices than when they regard the innovation as intervention by outsiders. In order to reduce the dimensional variation in BIW assemblies to world-class standards, changes in automobile manufacturers' technology base, manufacturing processes, and corporate culture must be pursued concurrently. The 2mm joint-venture project was the response of U.S. manufacturers and suppliers developing a coordinated and feasible approach in conjunction with assembly plant workers to solving the dimensional control problem.

2.0 ORGANIZATION OF THE 2mm PROJECT

The joint venture was formed by private industry for the purposes of applying for ATP funding and performing the 2mm Project. It consisted of a group of eight assembly line equipment and systems suppliers, faculty researchers and graduate students from the University of Michigan and Wayne State University, and GM and Chrysler. Although the Ford Motor Company was involved with preliminary discussions about the proposed 2mm Project, it did not agree to provisions in the joint venture agreement and did not join the joint venture. The assembly line producers participating in the research belong to the Auto Body Consortium (ABC). The ABC was formed with the general goal of pursuing solutions to the common problems encountered by the small assembly line builders, and with the specific task of coordinating the research and commercialization planning efforts of the 2mm Project.

GM and Chrysler own and operate assembly plants where automobiles are produced. Together, they produce approximately 48 percent of the automobiles sold in the U.S. The manufacturing and assembly equipment used in the assembly plants, however, is not produced by the automobile manufacturers. Instead, it is designed and built by the independent assembly line producers. The small assembly line producers build assembly lines according to the specifications of the automobile manufacturers. The 2mm Project involved automobile manufacturers, assembly line producers, and universities in developing solutions to the complex problem of dimensional variation and its causes.

2.1 Description of the Research Tasks in the 2mm Project

The 2mm Project was organized into 11 tasks that were grouped into four program areas. These areas were dimensional measurement technology, process control methodology, technology base for future body assembly systems, and technology transfer programs. These 11 research tasks were selected by the joint venture for the 2mm Project because they addressed the problems associated with dimensional variation of the BIW using a systems approach. The research tasks were conducted concurrently. Considerable communication of results occurred among the researchers performing the various tasks. This communication occurred due to the overlap of research staff across several tasks, and to the quarterly progress meetings attended by the research staff.

Each task contained at least one representative from industry who led the effort, and at least one university faculty member. Other industry engineers and graduate students were involved in the research being performed. The research was performed at university laboratories, development occurred at facilities of the assembly line producers, and data were collected and results were implemented at the assembly plants. Project Review Boards reviewed the progress of each task semiannually, and suggested future work as needed. Task progress reports were produced quarterly. An Executive Committee and Principal Investigator guided the overall progress of the 2mm Project.

A description of the technical goals and team participants of each of the tasks is presented in this section to provide background information for the economic impact assessments. As the focus of this analysis is the economic assessments, only a brief overview of the project's tasks is included in this report. An overview of the four program areas, the 11 research tasks, and the organizations involved in each task appears in Figure 2.1.

Figure 2.1: Summary of Tasks in the 2mm Project

PROGRAM AREA	STAMPING (Die)	TOOLING	ASSEMBLY (BIW: Body in White)
DIMENSIONAL MEASUREMENT TECHNOLOGY	Task 3: Measurement, Modeling, and Real-Time Numerically Controlled (NC) Path Generation for Free Form Surfaces Participants: *f M*	Task 2: Visibility Analysis and Sequencing Simulation for Tooling Certification Participants: *d h M*	Task 1: Computer Aided Design and Automated Setup for In-Line Optical Coordinate Measuring Machines (OCMM) Participants: *g M*
PROCESS CONTROL METHODOLOGY	Task 4: On-Site Measurement and Process Monitoring for Stamping Participants: *C M*	Task 5: Information Feedback for Tooling and Process Design Participants: *c*[1] *h C M*	Task 6: Process Navigators for Automobile Body Assembly Participants: *c M*
BODY ASSEMBLY TECHNOLOGY		Task 8: Optimal Non-Rigid Sheet Metal Part Holding Participants: *a M*	Task 7: Variability Characterization and Tolerance Budget Analysis for Body Manufacturing Participants: *C*[2] *G M*
		Task 9: Robust Design of Work-Holding Fixtures Participants: *a*[1] *e M*	Task 10: Optimization in Multiple Panel Fitting Participants: *b M*
TECHNOLOGY TRANSFER			Task 11: Technology Transfer Participants: *a C G W*

KEY TO PARTICIPANTS

Auto Body Consortium:
- *a* APX International
- *b* ASC Incorporated
- *c* Classic Design, Inc.
- *d* Detroit Center Tool (DCT)
- *e* ISI Automation Products Group
- *f* Modern Engineering
- *g* Perceptron
- *h* Progressive Tool & Industries, Inc. (PICO)

Auto Makers:
- *C* Chrysler Motors Corporation
- *G* General Motors Corporation

Universities:
- *M* University of Michigan
- *W* Wayne State University

[1] Participated only during the first quarter of the first year of the 2mm Project.
[2] Ceased participation in the third quarter of the second year of the 2mm Project.

2.1.1 Program Area 1: Dimensional Measurement Technology

There were three tasks in this program area.

Task 1: Computer-aided design (CAD) and automated setup for in-line optical coordinate measurement machines (OCMM).

The goal of this task was to eliminate the need for scribed prototype bodies to initially calibrate OCMMs. OCMMs are advanced non-contact measuring devices that accurately measure the size of features and openings on the BIW. The detailed data produced by the OCMMs are used to determine and document the dimensional variation of bodies in real time during assembly. When used, OCMMs are installed in the assembly line and calibrated for first use with a prototype automobile body that has been scribed with lines indicating where OCMM sensors should be positioned. This process requires the production of a full-scale body for use in the calibration. The research performed for this task involved developing an automated system that uses computer-aided design (CAD) files to select the positions for OCMM sensors, and then to calibrate the sensors. The results of this task reduce the time and effort required to set up the OCMMs for assembly line work, while maintaining or improving the accuracy of the measurement process. The use of the automated system reduces the time required to set up the OCMMs by an estimated 10 to 35 days. The OCMMS are set up on the automobile assembly line each time a new model is introduced, or design changes are made to an existing model.

Task 2: Visibility analysis and sequencing simulation for tooling certification.

Parts and subassemblies of the BIW are positioned and clamped during welding, cutting, and other assembly processes. The accurate positioning of parts is essential for dimensional variation to be reduced. Numerically controlled (NC) blocks and clamps are used to position and secure parts during assembly. The locations of the NC block and clamp fixtures are designated by the automobile manufacturer in their specifications for the assembly line equipment. A time-consuming measurement process occurs when the assembly line tooling is certified (e.g., checked to determine that it is accurately positioned). The research conducted for this task identified the optimal measurement sensors to certify NC blocks and clamps, and developed algorithms for efficiently locating the measurement devices during certification.

There are approximately 3,000 NC blocks used in an automobile body assembly line, and each block requires approximately one hour to certify. The results of this task were expected to reduce certification time by 30 percent while increasing positioning accuracy by 20 percent. Tool certification occurs many times during the life of the assembly line equipment: when the tooling is manufactured by the assembly line producer, when the automobile manufacturer certifies that the tooling meets specifications, when the tooling is installed at the assembly plant, and periodically to determine that the tooling is maintained at design specifications.

Task 3: Measurement, modeling, and real-time numerically controlled (NC) path generation for free-form surfaces.

Panels and sheet metal parts are formed using dies with complex surfaces that must be produced with tight tolerances. The measurement devices currently used to certify that the die surfaces meet tolerance requirements have limited accuracy, and take a considerable amount of time to execute the complete measurement of a die. In addition, the fabrication of complex dies requires an enormous amount of data to describe the die surface in the format required to guide the NC machine that produces the die. This research task developed a laser line scanning system that will accurately and quickly scan and certify die surfaces. Also, this task developed computer algorithms and methods to represent the paths that NC tools must follow to accurately and

quickly sculpt die surfaces. It is expected that the results of this research task will reduce the 15 to 25 hour measurement time for certifying dies by a factor of ten.

2.1.2 Program Area 2: Process Control Technology

There were three tasks in this program area.

Task 4: On-site measurement and process monitoring for stamping.

The production of sheet metal parts with accurately dimensioned features is difficult to achieve due to the flexibility of sheet metal. Many factors affect the dimensional variation of stamped sheet metal parts, including the material properties of the batch of sheet metal being stamped (e.g., Young's modulus), the handling of the sheet metal as it is transferred to the stamping press, the type of clamp used to hold the part and the positioning of the clamp fixtures, and the amount of pressure used to stamp the part. Subtle variations in these factors can cause large dimensional variation in the part, and subsequently in the BIW. Developing an understanding of the contribution of these factors, and others, to the dimensional variation of stamped parts is the objective of this research task.

The results of this task involve the creation of a knowledge base of causes associated with dimensional variation in fabricated parts during the stamping process.

Task 5: Information feedback for tooling and process design.

In some instances at some assembly plants, the lack of communication between assembly line operators and the designers of assembly line equipment has hindered the assembly line producers from collecting data from the laboratory of the assembly plant to make changes in their tooling that will diminish dimensional variations that occur during BIW assembly. This research task brought together the assembly line designers, parts suppliers, and the assembly line operators to gather information about the causes of dimensional variation in BIWs on the assembly line. This information describes the performance, failure modes, and failure frequencies of assembly line tooling; and OCMM data describe the resulting dimensional variation of the BIW. This evidence is collected at the assembly plant using a case study analysis to associate root causes with the resulting dimensional variation. The knowledge derived from these case studies, as well as the methodology used to produce the knowledge, was transferred to members of the joint venture and other companies via five "lessons learned" conferences. The knowledge is potentially useful to assembly line designers in designing future versions of tooling equipment. In addition, the case study methodology used to identify root causes of dimensional variation has become an important diagnostic tool for assembly line operators to identify and solve problems causing dimensional variation.

Task 6: Process navigators for automobile body assembly.

Existing automobile assembly plants incorporate sophisticated automated tooling and measuring equipment to assemble the BIW. The operation of this equipment and the data that are produced by the measurement systems are not generally used to manage the assembly process in a coherent fashion. This research task generated an integrated system that will acquire and use data in real time to characterize the performance of the assembly line in order to effectively manage dimensional variation. The research developed equipment and software to synthesize data from OCMMs and other measurement equipment. When the process navigator is introduced at assembly plants, the data from the measurement equipment will be analyzed using fault detection algorithms to identify when significant dimensional variation is occurring. Once undesirable variation is detected and characterized, a database of potential root causes will be automatically consulted to assist assembly line operators and engineers in addressing the problem. The ultimate results of this task provide a fully automated system for the monitoring, self-diagnosis, and

maintenance of the assembly line. The use of a process navigator is expected to reduce both the launch times of new assembly lines and the amount of time required to identify and solve causes of variational problems.

2.1.3 Program Area 3: Body Assembly Technology

There were four tasks in this program area.

Task 7: Variability characterization and tolerance budget analysis for body manufacturing.

The assembly process involves many complicated automated and manual operations that each have potential for contributing to the dimensional variation of the BIW. The analysis of which assembly processes contribute to different elements of dimensional variation is an important factor in reducing total dimensional variation. This task developed a case study methodology for analyzing and solving specific dimensional variation problems encountered in existing assembly lines. Use of the methodology has, to date, resulted in less than 2.0 mm of total dimensional variation at five automobile assembly plants. They include: Chrysler's Jefferson North assembly plant in Michigan; GM's Cadillac assembly plant at Hamtramck, Michigan; and GM's truck assembly plants at Shreveport, Louisiana, Moraine, Ohio, and Linden, New Jersey. This research task has also made important engineering contributions to the understanding of how dimensional variations in sheet metal parts accumulate during assembly to produce total dimensional variation.

Task 8: Optimal non-rigid sheet metal part holding.

The flexibility of sheet metal parts complicates the processes of locating, clamping, and supporting the parts during welding and machining. The choice of locations for work-holding fixtures (blocks and clamps) greatly affects the dimensional variation of sheet metal parts and the BIW. This research task developed techniques for selecting the optimal locations for work-holding devices based on an understanding of how the sheet metal part will flex in response to the holding devices. Finite element analysis and computer simulation are used to characterize the interaction between sheet metal and the locations of fixtures. The results of this research task assist assembly line designers in optimizing the locations of work-holding fixtures while they develop new assembly tooling to minimize dimensional variation on the assembly line.

Task 9: Robust design of work-holding fixtures.

This task, which addressed a problem that is similar to that of Task 8, developed an understanding of how sheet metal parts interact with different types of fixtures. This task created computer software that, given the locations of the holding fixtures (i.e., the locations determined with the methodology derived in Task 8), specifies the types or configuration of holding fixtures that will minimize dimensional variation. The results of this research task assist assembly line designers in optimizing the types of work-holding fixtures that will minimize dimensional variation for a specific sheet metal part. In addition, a new type of clamp, the SoftTouch clamp, has been developed by ISI Automation Products Group as a direct result of this research task.

Task 10: Optimization in multiple panel fitting.

Doors, hood, and decklid panels are attached to the assembled BIW during the final stage of assembly in the body shop. When a panel does not fit with appropriate gaps and flushness, it is fitted manually by adjusting hinges or bending the panel. These manual operations are not systematic, and often result in unintended dimensional variation. This research task developed hardware and software for a panel fitting process that optimizes the gaps and flushness of the attached panels. The results of this task reduce the need for manual fitting of panels, and thus reduce the dimensional variation associated with fitting.

2.1.4 Program Area 4: Commercialization Planning

This program area consisted of a single task.

Task 11: Technology Transfer.

The goal of this task was to synthesize the information, processes, and lessons learned from the 2mm Project, and incorporate the results into a user-friendly database that can be used effectively by potential users of the technical results. The technology transfer tasks will enable the companies involved to not only adopt the technology and methodology from the 2mm Project, but also establish the infrastructure for future, post-ATP, process improvements.

In addition to the development of a computer database, this task also has resulted in meetings between project participants and representatives from industries outside of the automobile industry, as well as the publishing of a newsletter that has documented the progress of the 2mm Project as the work has evolved.

3.0 EVALUATION OF THE IMPORTANCE OF GOVERNMENT INVOLVEMENT IN THE 2mm PROJECT JOINT VENTURE

Because the 2mm Project was conducted by a joint venture comprised of 12 organizations, the relationships among the various members of the joint venture are complex. Outside of the 2mm Project, the industrial participants often compete against or negotiate with each other on routine business matters. The different members might realistically expect notably different returns from their involvement in the project.

Under these circumstances, pulling the various organizations together in distinctive groups in each of the 11 tasks that comprise the project was a challenge. It appears unlikely that (a) this complex joint venture could have been formed and (b) funding for the research project could have been coordinated without direct administrative and financial involvement by the federal government.

There are several reasons. The principal impediments to formation of a successful joint venture, and how government involvement helped to overcome those impediments, are explained in Sections 3.1 through 3.6 below. The similarity between the joint venture that has been formed to perform the 2mm Project and other research consortia that have recently been formed among the domestic automobile manufacturers is discussed in Section 3.7.

3.1 Coordination Problems

The problem addressed by the 2mm project is a systems problem, requiring a high degree of coordination among a number of quite different organizations. The problem at issue could not be solved by these individual organizations acting alone, even if they strongly wished to solve the problem and were willing each to undertake a research task in their respective areas of expertise.

Forming large, complex research joint ventures to address a systems problem is, however, a daunting effort. Many obstacles must be overcome to organize and carry out a multi-task, interdisciplinary, integrated research effort across multiple organizations with differing missions, structures, and cultures. The ATP provided the impetus for the companies to overcome the coordination barriers and to come together to organize the research joint venture needed for the systems approach to solving the problem.

3.2 Impediments to Cooperation Among Automobile Manufacturers

Historically, the U.S. automobile industry has been resolutely scrutinized by the Antitrust Division of the Justice Department for possible anticompetitive activity. Employees of automobile companies have, therefore, been strongly warned to refrain from any interactions with competitors' employees that the Justice Department might consider suspect. Also, employees commonly have been required by their employers to sign disclaimers acknowledging their personal liability for any collaborative behavior that a federal court might judge illegal. These circumstances have spawned corporate cultures in which fear of antitrust action and consequent reluctance to engage in collaborative activity is deeply ingrained.

The fear of federal antitrust enforcement appears not to have been greatly reduced within the U.S. automobile industry by the passage of the National Cooperative Research Act of 1984. This law declares that businesses which notify the Department of Justice and Federal Trade Commission of

their cooperative ventures (i.e., collaborative research and development efforts on technologies involving sufficient technical uncertainties that their commercial potential cannot be reliably assessed) may qualify for single damage limitation on civil anti-trust liability.[3] However, shortly before the law was enacted, the domestic automobile manufacturers attempted to collaborate on research intended to develop emission control technologies that would comply with regulations on automotive emissions that had recently been promulgated by the State of California. The Justice Department initiated legal action to halt the cooperative research effort, and ultimately negotiated a 15-year consent decree that enjoined such collaboration. The consent decree was not completely withdrawn until 1986.

As a direct result of the long history of stringent antitrust enforcement in the automobile industry, engineers employed by any U.S. automobile manufacturer are wary about cooperating or even communicating with their counterparts in the other domestic automobile companies. In this distrustful environment, explicit involvement by the federal government may be essential to securing the participation of domestic automobile manufacturers in any collaborative research effort, particularly in complex, multi-task, multi-company efforts. The sponsorship and sharing of costs of the joint venture by ATP pursuant to eligibility criteria established by Congress provided the companies the necessary assurance that the project would be exempt from antitrust action. Joint research and development ventures selected for funding under the ATP must notify the Department of Justice or the Federal Trade Commission under the National Cooperative Research Act of 1984. As explained above, ATP projects which comply with the National Cooperative Research Act of 1984 may benefit from limited liability.

3.3 Impediments to Independent Funding of Research Projects by Assembly Line Equipment Manufacturers and Design Engineering Firms

The companies that supply assembly line equipment and design services to automobile manufacturers are, in general, small- and medium-sized companies with limited access to financial capital. They typically do not have research budgets that are large enough that they can independently fund the types of tasks that are being conducted in the 2mm Project.

3.4 Impediments to Cooperation Between Assembly Line Producers and Automobile Manufacturers

The automobile manufacturers benefit from research results that improve the design, development, or operational efficiency of motor vehicle assembly lines. The domestic automobile manufacturers, therefore, are possible sources of funding for research in these areas performed by assembly line producers.

Automobile manufacturers, however, are generally reluctant to fund research projects performed by their suppliers. If a project is successful, the company that has conducted the research will obtain a competitive advantage over its competitors in furnishing products or services to the automobile manufacturers. Under these circumstances, the funding bestows a degree of monopoly power to the companies that have received the funding when they subsequently compete for work solicited by the manufacturers who financed the research. The automobile manufacturers will incur increased costs, either directly or indirectly, as a result of any monopoly power that is created for individual assembly line producers by research that they fund. This tends to inhibit the funding of supplier research by domestic automobile manufacturers.

Conditions specified for the 2mm Project provided for: the freedom of all joint venture members to publish any research results in scientific journals; non-exclusive, royalty-free licensing of

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[3] U.S. Congress, National Cooperative Research Act of 1984 (15 U.S.C., 4301) as amended by National Cooperative Production Amendments of 1993 (P.L. 103-42, Section 2, 107 Stat. 117).

patents and copyrighted software, for internal use only, to all members of the joint venture and to NIST; and commercialization or sub-licensing of patents, and enhancement and re-marketing of software, upon negotiation of royalty-bearing licenses with the joint venture members. Such provisions for the sharing and dissemination of research results among members encouraged prospective members to cooperate in the formation of research and development joint ventures.

3.5 Impediments to Participation by Assembly Line Producers Due to Disproportionate Risk

The 2mm Project had a robust research design that entailed multiple potential ways of reducing dimensional variation. Although several of the component tasks have not yet attained all of their stated objectives, programmatic success has been achieved in all of the automobile assembly plants where task results have been adopted. Given the systems nature of the total project, the joint venture would fail to attain its intended reduction in dimensional variation of BIWs if several of the eleven component tasks are materially deficient in achieving their individual objectives.

Because the tasks are largely independent of each other, the technical risks associated with the individual tasks are essentially uncorrelated. As a result, the probability that several of the independent tasks might simultaneously be unsuccessful is much smaller than the probability that any of the individual tasks might be unsuccessful. The aggregate risk of failure associated with the entire portfolio of tasks is, therefore, lower than the risks associated with the individual tasks.

Moreover, the risks are not shared equally by the different members of the joint venture. The primary bearers of the risk of incomplete success on the individual tasks are the specific assembly line producers that have been directly involved in the tasks. To induce their participation in the 2mm Project, partial subsidization of their research activities was necessary to compensate them for bearing disproportionate risk. ATP's financial participation in the project, which helped members bring in university participation, decreased the financial outlay made by these companies and, hence, the net risk that was borne by individual members of the joint venture. It thereby increased the probability that a net gain would be realized by every organization associated with the 2mm Project.

3.6 Impediments to Participation by the Research Universities

Cooperative research projects between universities and industry typically involve industry providing funding for research initiatives that university researchers undertake because of their own intellectual curiosity. University researchers thus are accustomed to working on research projects where they have considerable discretion in selecting the specific problems that they are investigating.

The 2mm Project, by contrast, was an integrated research project in which the problems addressed in each component task were largely determined by the industrial participants, and were expressly designed to accomplish the overall objectives of the project. The university researchers consequently had much less discretion than usual in their detailed direction of the research activities. In the 2mm Project, they applied their expertise to a problem that directly affects industry, and they were required to develop solutions to the problem that are usable by industry in practice.

Concern about the possible industry restrictions on publication of research results that are based on proprietary information, however, might have deterred university researchers from participating in the project. Government involvement that allows publication unless it is specifically prohibited by the industry participants appears to have been instrumental in overcoming their reluctance to participate.

Also, graduate students who have worked on the project have received training to develop skills and knowledge that are very important to transferring the technical knowledge to industry. To date, four graduates of the University of Michigan have gained full-time employment with companies with which they previously worked on the 2mm Project.

3.7 Similarity to Other Automotive Research Consortia

The 2mm Project is not the only research and development joint venture in which the domestic automobile manufacturers are involved. Since 1988, pursuant to the passage of the National Cooperative Research Act of 1984, the nation's three major automobile manufacturers have formed 14 other research and development consortia. All of those joint ventures have been established in response to legislative mandates for either controlling emissions from, reducing fuel consumption by, or improving safety of automobiles. For example, the Low Emission Paint Consortium (LEPC) has been formed in anticipation of more stringent environmental regulation of automotive paint systems, principally the incremental control of volatile organic compounds (VOCs) under the Clean Air Act Amendments of 1990. There has thus been substantial government impetus to the creation of the 14 consortia.

The automobile manufacturers also established, in 1992, the U.S. Council for Automotive Research (USCAR). The purpose of USCAR is to direct and coordinate the research performed by the various consortia. The topics that the consortia have been investigating include: structural polymer composites, materials and materials processing, low emission paint, manufacturing emissions, reformulated gasoline and alternative fuels, automobile emission control technologies, natural gas vehicle technology, advanced storage batteries, electrical wiring components, occupant safety, vehicle recycling, computer-aided design and computer-aided manufacturing (CAD/CAM), supercomputer applications, and high speed serial data (HSSD) communication.

Government involvement in these research activities noticeably expanded on September 29, 1993, with the initiation of the Partnership for a New Generation of Vehicles (PNGV). The PNGV is a ten-year partnership between USCAR and the federal government. The federal agencies involved in the PNGV include: the Departments of Commerce, Defense, Energy, and Transportation; the U.S. Environmental Protection Agency; the National Aeronautics and Space Administration; and the National Science Foundation.

In every research and development joint venture that two or more domestic automobile manufacturers have entered, there has been substantial government involvement. Some, such as the 2mm Project and the United States Advanced Battery Consortium (USABC), have received direct government funding. Others, such as the LEPC, have been impelled by legislated requirements. Directly or indirectly, the federal government has been involved. We have been unable to identify any instances of collaborative research among domestic automobile manufacturers that have emerged without overt stimulation from the federal government.

4.0 IMPLEMENTATION OF 2mm PROJECT RESULTS BY JOINT VENTURE MEMBERS

Portions of the technologies and methodologies developed under the 2mm Project already have been transferred into operation at five motor vehicle assembly plants. They are: Chrysler's Jefferson North assembly plant in Michigan; GM's Cadillac assembly plant at Hamtramck, Michigan; and GM's truck assembly plants at Shreveport, Louisiana; Moraine, Ohio; and Linden, New Jersey. As a result of the interaction of assembly line operators and engineers with researchers performing 2mm Project tasks, the methodology for identifying and solving variation problems with assembly line tooling has also been successfully adopted in these five assembly plants.

In each assembly plant, data from in-line OCMM equipment provides indications of dimensional variations of BIWs. The occurrence of similar variations for multiple vehicles indicates a common cause due to variation in materials, parts, or changes in tooling. A systematic problem solving approach is used to identify the root cause of the particular variation. Then, the database of knowledge that is being continuously accumulated by the 2mm Project is consulted to devise a solution to the root cause. The OCMM data are then used to verify that the action taken has effectively solved the dimensional variation.

Each of these five assembly plants has realized or exceeded the goal of achieving 2.0 mm total dimensional variation for BIWs. The Shreveport and Linden GM truck assembly plants are operating at 1.7 mm total dimensional variation. Technology transfer is currently occurring within the automobile industry as a result of the interaction of industry engineers with the engineers and researchers involved with the ten research tasks in the Dimensional Measurement Technology, Process Control Methodology, and Body Assembly Technology program areas.

Other assembly plants that are not included within the scope of the 2mm Project, including Chrysler's minivan assembly plant in St. Louis, Missouri, have contracted with the University of Michigan to transfer the methodology for reducing dimensional variation. These assembly plants have learned the methodology through the University of Michigan or lessons-learned conferences, and are now beginning to implement the methodology to reduce dimensional variation and factory launch times. Thus, there is evidence that the results of the 2mm Project are being successfully commercialized within the automobile manufacturing industry.

Future reductions in dimensional variation and associated market impacts are expected as assembly line producers begin to incorporate results from the 2mm Project into new tooling equipment. Most of the results of the engineering research of the project have not yet been implemented in automobile assembly plants or other industrial sectors. The technical results, the theories of which have been communicated to the assembly line producers, are expected to be incorporated into future assembly line tooling. ISI-Automation Products Group has developed a new type of parts fixturing clamp, the SoftTouch clamp, as a result of this research project. The feasibility of commercializing this new clamp is currently being studied. In addition, the University of Michigan, Classic Design, Inc. and Perceptron, Inc. at the time of the study were discussing the possibility of commercializing software that was being developed as part of the research on process navigators for automobile body assembly (Task 6). University engineering researchers within and outside the joint venture, as well as the assembly line producers, recognize that the research results of the tasks will have future impacts on the subsequent assembly lines developed by these small companies.

Adoption of the results from the 2mm Project by other industries where they have potential application is possible in the future, as evidenced by discussions that members of the joint venture have had with representatives of aerospace, metal furniture, and appliance manufacturing companies.

5.0 NATURE OF IMPACTS ON THE AUTOMOBILE INDUSTRY OF ADOPTING THE 2mm PROJECT TECHNOLOGIES

The technologies and the methodology developed by the 2mm Project will directly affect Chrysler, GM, and other private industrial firms that adopt them in four ways. First, the production costs for the industries will decrease. Second, the quality of products manufactured by the industries will improve. Third, post-production maintenance costs will decrease. Fourth, launch times for new models or products will decrease. Moreover, as a result of their producing higher quality products at lower costs, the demand for outputs of the industries will increase over time. Thus, for the automobile industry, it is estimated that GM and Chrysler will increase their combined share of the market for automobiles. Similar market share benefits will likely also accrue in other industries where the technologies are adopted.

Production costs will be reduced for firms that adopt the case-study methodology for identifying and resolving problems occurring on the production line. The reduction in production costs will be associated with: less "down-time" during which technicians shut down the assembly line to find and correct problems with production equipment; reduced wastage of materials or partially assembled products that are determined to be of such poor quality that they should not be sold to consumers, and are discarded as scrap; reduced time spent by technicians who are assembling components onto the BIW that do not fit because of substantial dimensional variation; and reduced use of "clones", or other work-in-process, on the assembly-line floor.

The quality of the final product will be improved because dimensional variance will be identified and resolved quickly during assembly. The reduced dimensional variation of the BIW will result in the finished product having better fitting components. Since product quality is an important characteristic that potential buyers consider when purchasing a vehicle, the improvement in quality will be associated with larger sales, and larger market share. The improved product quality is also expected to result in lower maintenance costs to the automobile producers (while the automobile is covered by manufacturer warranty) and to consumers (after the warranty has expired).

Many other research tasks of the 2mm Project developed technologies that will be utilized by automobile producers during the construction of the assembly line for new automobile models. The technologies will assist the assembly line producers to fabricate the assembly line equipment more quickly, and to reduce the length of time required for the completed assembly line to produce vehicles with acceptably low dimensional variation. The more quickly the automobile producers can launch a new automobile model, the larger the sales of the new model.

In summary, the types of impacts identified are the following:

- Production cost savings
- Maintenance cost savings
- Product quality improvements
- Shorter set-up time for launch of new models

Part II: Estimating the Economic Impacts of the 2mm Project

6.0 MODELING AND DATA ESTIMATION

Initial estimates of some of the economic impacts of the 2mm Project were estimated, based on expert judgments of the expected future changes in costs and final demands that will result from the adoption of technologies developed by the 2mm Project in automobile assembly plants. These judgments were obtained by CONSAD from manufacturing engineers involved with the 2mm Project's research tasks, from industry and trade experts, from market analysts, and from economists with experience in the automobile and discrete manufacturing industries. The individual sources of information and judgments, and information for individual plants and firms adopting technologies that have resulted from the 2mm Project, are not cited because of the proprietary and confidential nature of the data about current and expected cost savings and expected product demands. Other factors that could affect cost or demand are assumed to have remained constant.

Reflecting different approaches to estimation, separate estimates are developed for the economic impacts of cost reductions resulting from productivity improvements and the economic impacts of demand increases. Different approaches were taken because it was CONSAD's view that attempts to estimate within the context of the REMI model the effects of decreases in expected costs of the magnitude projected for the automobile industry, although sizable, would be infeasible. This is because the changes are likely too small in relation to total U.S. economic activity to have a reasonable expectation of being isolated and hence measured. In contrast, it was CONSAD's view that it **was** feasible within the scope and budget of the project to allow assessment of the projects quality improvement impacts in relation to total U.S. economic activity using the REMI model.

The estimated economic impacts of the expected reduction in production and maintenance costs are measured in terms of the total cost savings that might be realized by the automobile manufacturers as a result of those cost reductions. The cost reductions comprise substantial cost savings for the manufacturers, some portion of which may be shared with customers. The cost savings provide manufacturers with increased flexibility in applying pricing strategies that influence their market shares and profits. Equivalently, the cost decreases provide the automobile manufacturer with the option of adding more features to cars without increasing price. Allocating the cost savings between producer and consumer was not attempted.

The estimated economic impacts of the increases in market demand that are expected to be stimulated by improvements in product quality are measured in terms of the changes in total industry output and total private employment that are projected to result from those demand increases, other factors being constant. A macroeconomic model is used to estimate the economic impacts from increased market demand.

Implementation of the technologies developed by the 2mm Project will also substantially decrease the time required to launch the assembly of new automobile models. Industry experts assert that the reduction in launch times will generate sizable increases in sales for automobile manufacturers' popular new models. The available information is insufficient, however, for reliable estimation of the magnitude of the dollar sales increases.

6.1 Expert Estimates

Because the technologies developed by the 2mm Project are new, their impacts on industrial production and economic activity are not yet revealed in the extant empirical data on industrial performance. Therefore, to obtain realistic estimates of the likely magnitudes of those impacts, judgments about the anticipated consequences of applying the technologies were elicited from two groups of experts.

First, experts who are knowledgeable about the substance of the technologies have been interviewed to obtain their judgments about how practical application of the technologies will affect the production processes (e.g., the utilization rates of specific inputs and the resulting production costs) and the quality of products in firms that adopt the technologies. The experts who have been interviewed in this regard consist primarily of university researchers and manufacturing engineers who have been directly involved in research tasks performed on the 2mm Project, and technicians and engineers who have been involved with the initial implementation of project results at five automobile assembly plants.

Second, experts who are knowledgeable about the industries and markets in which the technologies will likely be used have been interviewed to obtain their judgments about the expected extent and rate of adoption of the technologies in those industries and markets. The experts who have been contacted for this purpose include industry and trade experts, market analysts, and economists who have experience relating to the motor vehicle and discrete manufacturing industries.

The plausibility of the judgments provided by the two groups of experts has then been evaluated by examining the coherence among the judgments provided by the various experts in each group. In addition, to the degree possible, the judgments have been compared to the available empirical data on the outcomes of the initial applications of the technologies in actual industrial situations (i.e., in motor vehicle assembly plants where the technologies are presently implemented), and to published evidence on the outcomes of applying similar technologies in comparable circumstances.

6.2 Macroeconomic Interindustry Model of the National Economy

In this task, a macroeconomic interindustry model of the national economy has been employed to estimate the impacts on the U.S. economy of increased demand from quality improvements resulting from use of the new technologies in the U.S. automobile industry. This has involved expressing where feasible the estimates of direct economic impacts, described in Section 5.0, in terms of changes in the values of specific parameters in the macroeconomic interindustry model. The revised parameter values then became inputs into the model, and the model has been run to simulate the effects that adoption of the technologies by the automobile industry will have on economic activity. These effects include impacts on industrial sectors that supply inputs to, or purchase outputs from, those in which the technologies are directly applied, and consequent feedback effects on demands for various industries and markets. The model also provides forecasts of the aggregate changes in national economic activity that will be stimulated by the use of the technologies, including changes in total industrial output and total private employment. The economic impacts of using the new technologies have been estimated as the difference between the forecasts derived with the revised parameter values and the forecasts derived with the initial baseline values.

The macroeconomic interindustry model that has been used in this study is the Regional Economic Models, Inc. (REMI's) Economic and Demographic Forecasting and Simulation 53-Sector (EDFS-53) Model of the national economy.[4] The model contains numerous structural equations that describe: production and output; population and the supply of labor; demands for labor and capital (including residential structures, nonresidential structures, and equipment); and wages, prices and profits. Interindustry transactions are represented by an input-output structure based on the input-output tables compiled by the Bureau of Economic Analysis (BEA). Equations representing behavioral relationships based on economic theory endogenously determine feedbacks on final demands among different industries in the economy. The model also characterizes substitution among inputs in response to changes in their relative costs, and wage

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[4] For further description of the REMI model, see George I. Treyz, *Regional Economic Modeling.*

adjustments in response to changes in labor market conditions. Forecasts of economic activity are produced for 53 economic sectors (including 49 private nonfarm industries, three government sectors, and the farm sector) and for the aggregate national economy.

7.0 ESTIMATED BENEFITS OF AUTOMOTIVE PRODUCTION COST SAVINGS

The implementation of the results of the 2mm Project at automobile assembly plants will reduce the production costs for these plants as described in Section 5.0. Engineers at GM's truck assembly plant in Linden, New Jersey, and 2mm Project researchers involved with the technology transfer at Chrysler's Jefferson North assembly plant estimate that net production costs – that is, production costs per car less the costs per car of implementing the 2mm technology – at those facilities have been reduced by approximately \$10 to \$25 per vehicle as a direct consequence of implementing results from the 2mm Project. The production cost savings are expected to vary at each assembly plant according to the current level of total BIW dimensional variation. The savings represent approximately one-sixth of one percent of the total production costs for an "average" automobile produced in the U.S. The reduction in production costs begins once the key technological components are in place and the automobile manufacturers' manufacturing engineers and line operators have adopted the 2mm Project's methodology. The production cost savings result from improved labor productivity and reduced waste during the assembly process.

The price of automobiles is highly inelastic with respect to changes in production costs. The automobile industry consists of a relatively small number of firms that produce highly differentiated products. When devising pricing strategies, automobile manufacturers take into account the anticipated responses of their competitors[5]. They also use short-term pricing tactics that include factory rebates and temporary product sales to compete for customers based on price. It is, therefore, unlikely that the projected decrease in production costs will directly stimulate a discernable reduction in the price of automobiles. However, since the market for automobiles is very competitive, the results of the 2mm Project will allow the automobile manufacturers who adopt the dimensional variation technologies to be more flexible in responding to changes in the market for automobiles.

To the degree that the price of automobiles does not decline in response to the projected decrease in production costs, the automobile manufacturers will realize increased profits. Industry experts estimate that, over the next five years, all of GM's and Chrysler's assembly plants will adopt the results of the 2mm Project. Upon full adoption, the estimated \$10 to \$25 net savings that GM and Chrysler will realize on each of the approximately 6.5 million cars and light trucks that they produce annually will amount to an overall net savings of approximately \$65 million to \$160 million annually.

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[5] Fellner, W. J., *Competition Among the Few*, New York : Augustus M. Kelley reprints of economic classics, 1960; Sherman, R., *Oligopoly*, Lexington, MA: D. C. Heath and Company, 1972.

8.0 ESTIMATED BENEFITS OF AUTOMOTIVE MAINTENANCE COST SAVINGS

In addition to affecting production costs, the reduction in dimensional variation that will be achieved due to automobile assembly plants' adopting the results of the 2mm Project will also reduce the amount of maintenance work that will be necessary to repair automobiles. While an automobile is under warranty, the automobile manufacturer compensates the automobile dealer who performs repairs on the automobile. According to representatives of GM and Chrysler, approximately $500 of the retail price of a new automobile, on average, is associated with the expected amount of maintenance work that will need to be performed while the automobile is covered by the manufacturer's warranty. Only a portion of this maintenance work is necessitated by the quality of the BIW; the rest involves repairs to other components, such as the powertrain, the electrical and computer systems, and interior and exterior trim. Maintenance costs vary among automobile models. No data currently are available to characterize how much maintenance work will be avoided in the future due to the reduction in dimensional variation of BIWs that will result from the implementation of 2mm Project results. The magnitude of the cost savings associated with avoiding future maintenance work is clearly lower than the hypothetical limit of approximately $500 per vehicle, but is not known at this time.

Precise estimates may be possible in the future, as automobiles that are assembled using technologies developed by the 2mm Project complete their warranty period. At present, however, estimates of the reduction in maintenance costs that will be achieved for automobiles produced in assembly plants where the results of the 2mm Project have been implemented are necessarily imprecise. The average decrease will likely lie in the range of $50 to $100 per vehicle.

If, as industry experts anticipate, the project's results are adopted in all of GM's and Chrysler's assembly plants within five years, maintenance cost savings will ultimately be realized on all of the approximately 6.5 million cars and light trucks produced in those plants annually. Thus, over the useful lives of the vehicles produced in those assembly plants during a year, total savings in maintenance costs ranging from $325 million to $650 million will be obtained as a result of the 2mm Project. If sales of vehicles assembled in the plants remain relatively stable over time, this level of total cost savings will eventually be realized annually, on average. Much of the savings will accrue to the automobile manufacturers during the vehicles' warranty periods; the balance will accrue to the vehicles' owners thereafter.

9.0 ESTIMATED BENEFITS OF AUTOMOBILE QUALITY IMPROVEMENTS (PRELIMINARY PROJECTIONS OF THE MACROECONOMIC IMPACTS BASED ON EXPERT-PREDICTED CHANGES IN MARKET SHARE)

The largest impact of the 2mm Project anticipated by the joint venture members is an increase in market share (relative to what it would have been without the project) for U.S.-made automobiles due to improved product quality. Currently, industry experts believe that, on balance, the styling, performance, and price of automobiles manufactured by U.S. companies are comparable to those of automobiles produced by foreign companies. However, the quality of American automobiles, measured through customer surveys (e.g., J. D. Powers and Associates), is perceived to be less than that of foreign-made automobiles.

Figures 9.1 and 9.2 present estimates of the increases in total industrial output and total private employment in the U.S. that are expected to be stimulated by the improvements in product quality achieved by U.S. automobile manufacturers through their adoption of technologies from the 2mm Project. Although substantial economic impacts are associated with the direct effects of the 2mm Project on the automobile manufacturers, even larger estimated impacts are realized by the entire U.S. economy because of the indirect effect that a change in sales in the automobile industry will have on many other business sectors. These economic impacts were estimated in simulations performed using the Regional Economic Models, Inc. (REMI) national econometric model. Underlying the estimates are judgments by joint venture members and other automobile industry experts about the increase in market share that will be elicited by the improvements in automobile quality.

Only the lower-bound scenario has been simulated to examine the estimates for the change in market share for American automobiles that the experts expect will result from the 2mm Project. The scenario analysis assumes that the total size of the market for automobiles will not be affected by the project, but that the percentage of total U. S. automobile sales captured by GM and Chrysler will be higher (relative to the percentage without the new technologies) at the expense of foreign-made automobiles. The lower-bound scenario assumes that the combined market share of GM and Chrysler will increase (relative to the baseline) by 1.0 percent. The value represents the smallest estimate obtained by CONSAD from industry experts. The experts, who provided data and judgments regarding estimated changes in market share, referred to past instances when a short-term change in the perceived quality of an automobile model resulted in a shift in market share for the particular model relative to competitors' models.

Projections of the impact of the expected change in product quality on sales of U.S. produced automobiles are developed by estimating the increase in sales of domestically produced automobiles that will result from an increase in market share for GM and Chrysler. For a given level of increase in market share for GM and Chrysler, the change in sales of domestically produced automobiles is estimated to be equal to the increase in market share for GM and Chrysler multiplied by the ratio of the current market share for imported automobiles to the total U.S. market share for automobiles NOT produced by GM or Chrysler. This approach is based on the assumption that increased market share for GM and Chrysler that displaces the sales of imported automobiles will result in an increase in economic activity in the U.S. In contrast, it is assumed that increased market share for GM and Chrysler that displaces domestically produced automobiles will have no net effect on economic activity in the U.S. It is further assumed that Ford's market share will remain constant during the period of analysis. This assumption seems conservative given that all the U.S. assemblers share the same supplier base. (Estimates of U.S. automobile sales for domestically produced and imported foreign-made automobiles were obtained from industry reports of total automobile sales.)

The projected increase in market share was introduced as an input into the REMI model, and the corresponding future changes in industrial output and private sector employment were estimated. Estimates are presented for the years 1995 to 2000. Impact estimates for years after 2000 are not reported because it is difficult to predict developments in automobile production technology that far into the future.

Figure 9.1 shows that the quality improvements of the 2mm technologies in the automobile industry are projected – using the REMI model and the lower end of the range of estimated market-share gains – to stimulate an increase in total industrial output in the year 2000 of more than $3 billion. The cumulative output increase between 1995 and 2000 is projected in excess of $8 billion, again based on the lower end of the range of assumed market share response.

The REMI model was also used to project how the quality gains might affect employment. As shown in figure 9.2, quality improvements in automobiles — and the assumed resulting increase in market share of domestic producers at the expense of imports — may stimulate thousands of new jobs across the economy, taking into account inter-industry effects and assuming that the economy is able to absorb new jobs. The REMI estimates are based on the assumption of a Keynesian economic response to the modeled changes in product quality which permits an increase in employment to occur without the assumption of an immediate constricting action in monetary policy to offset the employment gains. Of course, to the extent that it were assumed that the economy is operating at full employment with strong wage pressures over this period, there would be a tendency for newly created jobs to be filled by workers moving from existing jobs, a tightening in monetary policy, and less opportunity for a net gain in total national employment.

10.0 BENEFITS OF POTENTIAL COST SAVINGS AND QUALITY IMPROVEMENTS IN OTHER INDUSTRIES

When the original proposal for the 2mm Project was being developed, it was anticipated that the technologies and processes to be developed as part of the project would have potential application in the aerospace, appliance, and metal furniture production industries. During the course of the project, representatives of several of these industries that manufacture products requiring the automated assembly of metal parts have contacted the ABC and researchers at the University of Michigan to learn about the areas of research and the technical results of the 2mm Project, and appear interested in the potential use of the results of the 2MM Project to improve their product quality.

Because the production processes and tools used by the aerospace, appliance, and metal furniture industries are different from those used by the automobile industry, the technical results of the 2mm Project must be adapted before they can be applied commercially in these industries. The methodology for reducing dimensional variation, however, may have direct, immediate application. At present, no industry other than the automobile industry has applied the technologies that have resulted from the 2mm Project.

Since these other industries do not incorporate levels of automation as high as those in the automobile industry, the expected savings in production costs per unit of output are not as large as in automobile assembly. Industry experts believe, however, that the potential production cost savings are substantial. In addition, they expect that the reduction in dimensional variation during the production of airplanes, appliances, and metal furniture may have substantial impacts on product quality, but at this time there are no specific estimates of how reduced dimensional variation will translate into cost and price reductions or market-share increases in these industries.

11.0 LIMITATIONS AND RECOMMENDATIONS FOR FUTURE CASE STUDIES

The methodology used for this case-study analysis has relied on expert judgments and limited available data to characterize and estimate the economic impacts of the technologies developed by the 2mm Project, and implemented by automobile manufacturers. The estimates of market-share changes from quality improvements for automobile manufacturers were used as inputs in the REMI model to project the resulting economic impact on the economy of the entire nation. The use of experts was necessary because of the lack of extant empirical data describing: the direct impacts of the 2mm Project technologies on the production processes across different assembly plants (estimates were based on the experience of several plants); the rate of adoption of the technologies by automobile manufacturers; and the magnitude of impact of the resulting increase in product quality on the sales of automobiles. These data must be estimated because the new technologies developed by the 2mm Project are just now beginning to be adopted at automobile assembly plants in the U.S.

The use of judgments from experts who are familiar with the technologies developed as part of the 2mm Project may result in biases in the results of this analysis by CONSAD. But the existence, type, and size of possible bias cannot be determined at this time. When more facilities have adopted the technologies, then data can be collected and compared with the expert judgment to gauge the accuracy of the estimates used in this analysis.

Economic projections, in general, involve estimates of how individuals and firms will behave in the future under circumstances that may not be well-characterized by existing available data. Thus, all such projections rely on expert judgment to some extent. In order to reduce the possibility of bias in the estimates of direct impacts, it is important to obtain judgments from many experts with different perspectives on the research project being analyzed. For the purposes of future case-study analyses, it may be fruitful to spend the additional time and resources necessary to develop a committee of experts who are knowledgeable about the research project being studied, and to inform the committee of the progress of the project from the beginning. The appropriate choice of experts, the proper briefing of the experts on the progress of the research project, and the broad availability to the experts of economic data from firms that develop and adopt the resulting technologies will improve the credibility of the expert judgments obtained to describe direct impacts. Use of the Delphi technique, or similar techniques, may further improve the quality of expert judgment.

An additional obstacle to performing case studies is the need for data which is sometimes viewed as proprietary by the companies. Since the existing data and information describing the specific impacts of the technologies developed as part of the 2mm Project pertain to specific company facilities that have already adopted part of the technologies, these data were considered proprietary in nature, to be treated as commercial secrets. Thus, the full details of the data used in estimating cost savings and market share have not been documented here, but have been used to guide the estimates and choice of parameter values used in the analysis. This situation is not uncommon in performing industrial case studies, and will probably not be addressed differently in other case study analyses since it is the nature of firms in competition to maintain certain information as proprietary. However, it might be useful in future grants to make more explicit during the early stages of the research project the type of information that would be required from the participants for case-study evaluations, and to try to find common ground up front that would later meet the ATP's need for specific information to support evaluation of that project and the company's need to protect proprietary information. (For projects funded by the ATP since 1992, a systematic approach is in place for collecting project data, but the 2mm Project predates the implementation of the ATP's "Business Reporting System." Even with ATP's Business Reporting System in place, there will likely be unique pieces of data needed for case studies that will be missing unless the scoping of data requirements is performed in advance for each project and negotiated with the companies up-front.

A further limitation was that not all of the observed effects of the technology on the automobile industry were modeled using the REMI model. For this case-study analysis, although the auto production cost changes associated with the adoption of the technologies developed by the 2mm Project are sizable, these costs are relatively small compared to the total production costs of the automobile manufacturing industry. The analytic content of the 53-sector REMI model is not detailed enough to project the total impact of the production cost savings on the entire economy. But, as presented in the previous section, the REMI model is an appropriate analytic tool to estimate the impacts of changes in market share of the size observed in this study. In future case-studies, a preliminary assessment to ascertain the optimal analytic tools to be used to project different types of economic impacts, for different types of industries, would be helpful.

Finally the omission of quantified estimates of the economic impacts that adoption of the technologies by the other manufacturing sectors might have is a limitation with respect to total potential impact of the generic technologies developed. At this early stage, there is simply too little information on the likely rate of adoption of the technologies by other manufacturing sectors, and on the resulting impacts on production costs and product quality and sales in those other sectors.

For this experimental analysis, case-study budget constraints did not allow further refinements of the data and assumptions. Future case studies analyzing the impacts of new technologies for which there is little empirical data would benefit from an allowance for more supporting research.

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Figure 9.1 Estimated Increase in Total Industrial Output Due to the Adoption of 2 MM Program Results by Automobile Industry Based on Assumed 1.0 Percent Increase in Market Share

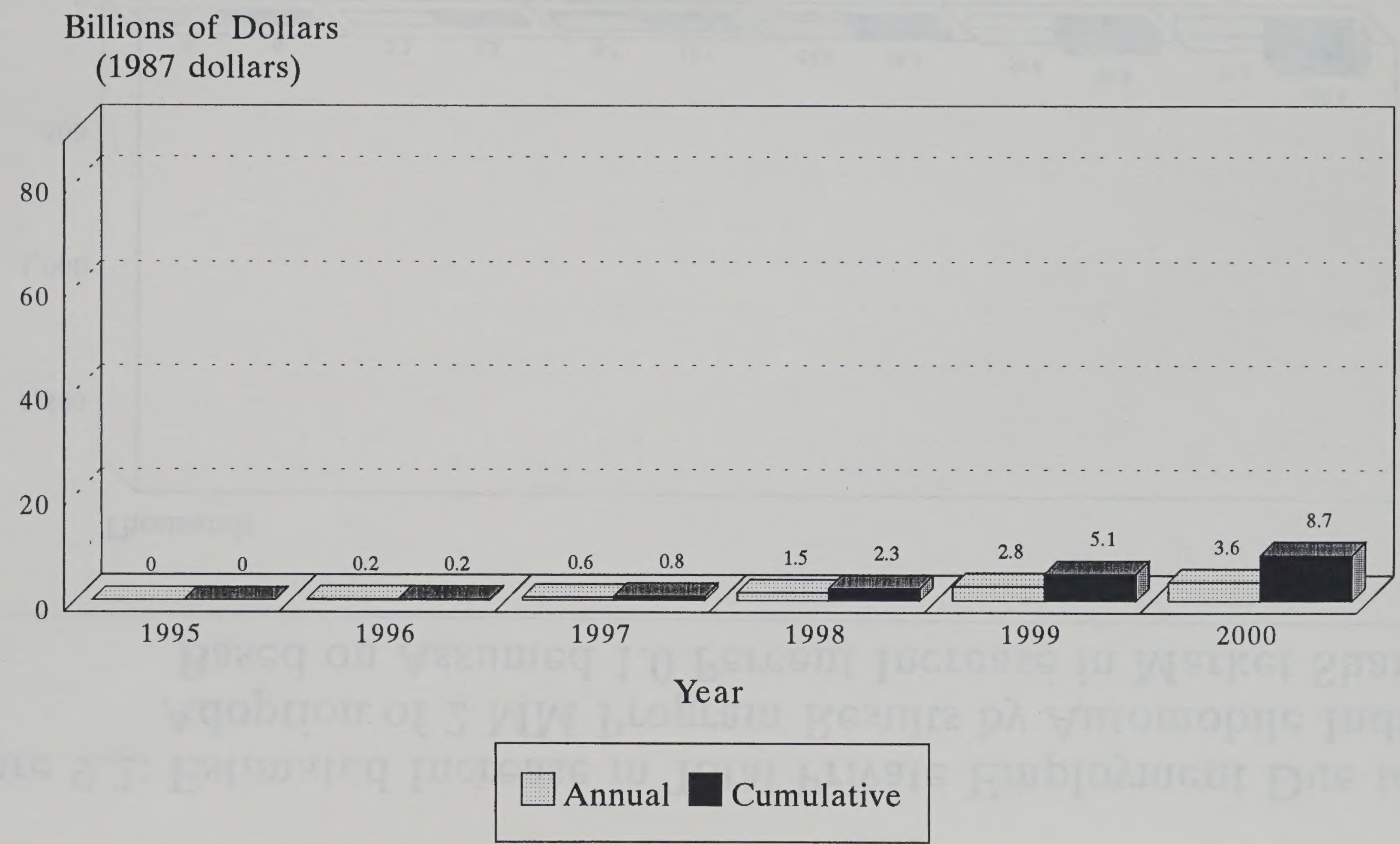

Figure 9.2: Estimated Increase in Total Private Employment Due to the Adoption of 2 MM Program Results by Automobile Industry Based on Assumed 1.0 Percent Increase in Market Share